The Effect of Clustered Scatterers on Volume Reverberation

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LONG-TERM GOALS

The long term goal of this work is to further the understanding of how clustering in clouds of discrete scatterers has an effect on both forward propagating and backscattered acoustic fields. Clustering is considered to be present when there are spatially dependent correlations in the fluctuating positions of the scatterers. For example, bubble clouds created by oceanic breaking waves have been observed to exhibit clustering at a level that would have a significant impact on the forward propagating acoustic field. Clustering is also expected to be present in fish aggregations (e.g., nearest neighbor distances, school morphologies driven by behavior, inter-school spacing), and consequently should be accounted for when examining bioclutter. This work is based on a) refining theoretical approaches so that they include clustering; and b) observing clustering in the important classes of discrete volume scatterers in the ocean.

OBJECTIVES

This objectives of this research are to 1) further develop the basic constructs that have previously been used for examining clustering amongst bubbles so that it can be used to examine reverberation caused by clustering in fish aggregations at mid- to low-frequencies (i.e., at or near swim bladder resonances), and 2) leverage existing fisheries high resolution multibeam sonar data collection efforts (or other similar efforts) to look for clustering within, or between, aggregations of fish, and to then to predict the effect of this clustering on volume reverberation.

APPROACH

This work seeks to extend the previous work examining clustering in clouds of bubbles [Weber et al. 2007, Weber 2008] by looking specifically at backscatter and volume reverberation. A modeling component used previously by Weber et al. [2007], which is based on the multiple scattering work of Foldy [1945], examines acoustic fields in free-space (i.e., short range or deep water scenarios). This has been modified to incorporate simple surface scattered paths between a monstatic sonar and a school of scatterers (fish) several water depths away (to date, scattering chains between the fish themselves assume no interactions with the boundaries). Key questions are related to how such

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modifications will change the statistics of the observed bioclutter: will multipath increase or decrease the importance of multiple scattering when compared with the single scattering approximation; will image sources and "image fish" increase the importance of clustering (or even create it where there was previously none); etc.

In addition, existing fisheries multibeam sonar data collection efforts are being leveraged to look for clustering within aggregations of fish. This effort takes advantage of existing data collection efforts being conducted using other funding mechanisms. Data sets that will be used in this work cover a range of scales providing, at separate times and for separate species, direct quantification of clustering ranging from the resolution of the fish (i.e., nearest neighbor spacing) to instantaneous observations of inter-school spacing. These data sets include

- August, 2009: Juvenile bluefin tuna imaged using a 400 kHz Reson 7125 multibeam sonar, in which individuals are resolved. This data was collected in collaboration with Molly Lutcavage from the UNH Large Pelagics Research Center.
- Summer/Fall 2008/2009: Atlantic herring schools imaged using a 25 kHz omni-directional sonar (SP90), in which multiple schools are simultaneously observed. This data was collected in collaboration with Jason Stockwell from the Gulf of Maine Research Institute and Mike Jech from the Northeast Fisheries Science Center.
- October 2009: Rockfish schools imaged using a 100 kHz Simrad ME70 multibeam sonar, in which school morphology (clustering within the school) will be examined. This data will be collected in collaboration with Chris Wilson and Chris Rooper from the Alaska Fisheries Science Center.

The afore-mentioned data will be incorporated into the modeling component in order to further the understanding of the effect of fish clustering on volume reverberation, using a similar methodologies to that described by Weber et al. [2007].

WORK COMPLETED

The focus of the work completed in 2010 has been on moving toward a more realistic scattering model for schools of juvenile bluefin tuna (*Thunnus thynnus*), a highly mobile pelagic species found throughout both the western and eastern atlantic [Gibbs and Collette, 1966]. Bluefin tuna are slightly more dense than seawater and utilize a gas-filled swim bladder to maintain swimming depths at slow speeds [Magnuson, 1973]. The swim bladder, which has a size dependent mechanical resonance, is expected to dominate the acoustic response at low-mid frequencies. Although it is known that the swim bladder of individual tuna are highly variable in both their shape and size [Gibbs and Collette, 1966], no metrics describing this variability appear to be available in the published literature. For the purposes of this work, which is designed to match observations of 80-100 cm size bluefin tuna, a swim bladder volume of 250 cc was used based on the work of Schaeffer and Oliver [1999] who examined the swim bladder of yellowfin tuna (*Thunus albacores*). Despite the possible difference between species, this is thought to be a reasonable approximation given that both species would have needed to develop a swim bladder for the same mechanical reasons outlined by Magnuson [1973]. The 250 cc swim bladder volume corresponds approximately to a 100 cm length juvenile tuna. The target strength for an individual tuna (swim bladder) of this size was estimated using the model described by Love [1978].

Two basic school models have been examined, both of which have the general morphology of an oblate spheroid. In the first model the fish are oriented randomly throughout the school, without maintaining a nearest neighbor distance or any of the behavior that would define a school in the true sense of the word (that is, this would be more accurately described as an *aggregation* of fish). In the second model the school maintains a uniform *average* spacing throughout: the fish are constrained to fixed positions, but allowed to randomly depart some small distance (a quarter of a body length) from these positions. These two school models are used as the input to three different types of acoustic scattering models:

1) An incoherent summation of the scattering strength σ, $\sum_i \sigma_i$, in which the only random component is the depth of the tuna and its effect on the swim bladder acoustic response.
2) A coherent single scattering approximation, $|\sum_i p_o s_i G(r, r_i)|^2$, in which both the effect of the depth of the tuna and its relative distance from a monostatic sonar are considered.
3) A coherent multiple scattering approximation, $\left|\sum_i p^i s_i G(r, r_i)\right|^2$, which is similar to the second model but is exact for a given realization of point scatterers.

The difference between models 2) and 3) are the incident pressure at each individual tuna: in model 2) only the fish-free incident pressure is used, and in model 3) the contributions from each of the other fish are accounted for. These models are used in a Monte Carlo simulation using either 2,500 or 10,000 realizations, depending on the granularity of the model parameters (number of fish, frequency). Up to 500 fish are used for the model runs, and the frequencies are selected to correspond to that of a mid-frequency sonar.

The model runs described above have been placed in the context of observed schools of juvenile bluefin tuna schools using aerial imagery and high frequency multibeam data, data that was collected concurrently in the summer of 2009. The majority of the aerial imagery has been processed in order to get the number of fish, nearest neighbor distance (as a function of body length), and similar metrics that can be directly incorporated and/or compared to the model runs. Similarly, a significant amount of the multibeam data, which offers a vertical slice that augments the planar view given by the aerial imagery, has been processed in order to provide the horizontal morphology of the fish. These data provide a useful context that helps to gauge the expectation of encountering a school – and therefore an acoustic scattering scenario – similar to that which has been modeled.

RESULTS

Fully Random (Poisson Distributed) Fish

The frequency dependent target strength for an individual tuna is given in Figure 1. The target strength at resonance (~100 Hz) is approximately 1 dB, and ranges from -17 to -20 dB at the frequencies examined here. The model used to derive the target strength is given by Love [1978], and this same model is used to provide the complex scattering amplitude that acts as the 'kernal' for both the single and multiple scattering models.

Figure 2 illustrates the comparison between the different acoustic scattering models for fully random (Poisson distributed) fish 'schools' (i.e., no order, such as a nearest neighbor distance, has been imposed). The school morphology is fixed: an oblate spheroid with major axis of 20 m and minor axis

of 4 m. At the high end of the frequencies examined (10 kHz), the multiple scattering and single scattering results are indistinguishable, and are nearly identical to the incoherent summation of scattering strengths. At lower frequencies, where the scattering response of the tuna is greater, the multiple scattering solution begins to depart from the single scattering solution when the number of fish is high (say, greater than 200). In this instance the single scattering solution overestimates the true target strength of the school. Overall, the difference between the single scattering and multiple scattering solutions is generally small (less than a dB except at low frequencies and large numbers of fish) for the fully random fish schools, as shown in Figure 3.

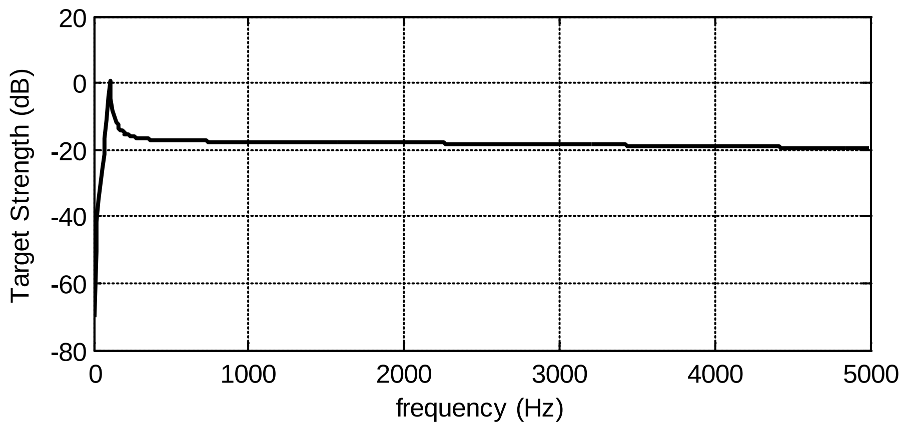

Figure 1. The modeled target strength of an individual 100 cm bluefin tuna (swimbladder volume: 250 cc) at a depth of 2 m.

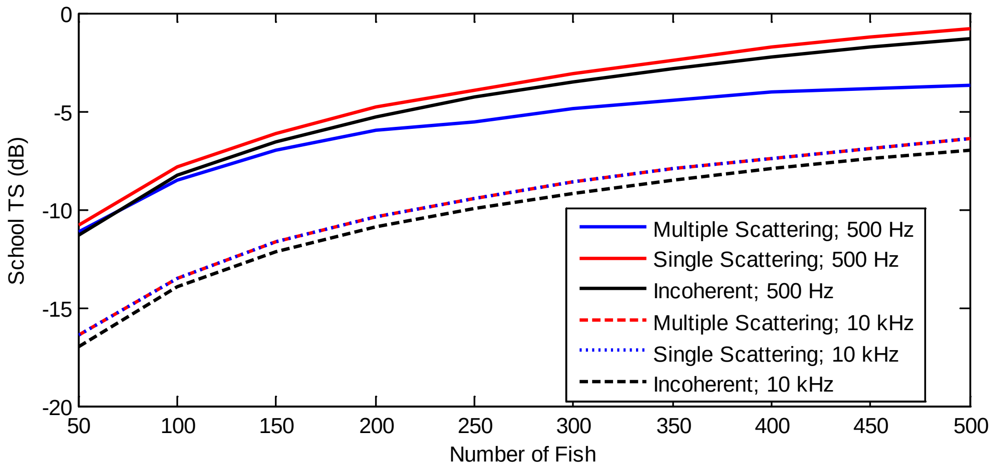

Figure 2. Example model outputs for the fully random (Poisson distributed) fish 'schools'.

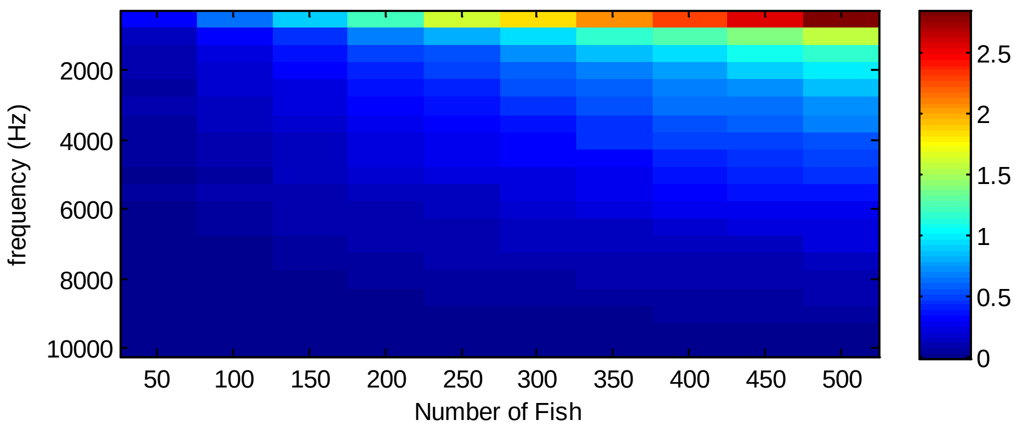

Figure 3. The difference between target strengths calculated using the single scattering and multiple scattering models (TS_{ss} – TS_{ms}).

Clustered Fish

In order to examine the effect of clustering (as defined by Weber, 2007) on the tuna schools, the fully random model was adjusted so that the fish were – on average – evenly distributed throughout the school in both horizonal dimensions while maintaining the same oblate spheroid school morphology. The fish were allowed to randomly vary their position by up to 0.25 m (1/4 of their estimated size) about their fixed grid location. Introducing this type of order into the school introduces a resonant behavior that is observable in both the single and multple scattering models, but not apparent in the incoherent model. This resonance behavior is explainable as school resonances, which should appear when the spacing is an integer multiple of a half wavelength (note that this model is for backscatter). The school dimensions have been fixed (they are identical to that used for the totally random school), and so the nearest neighbor distance changes as a function of the number of fish. The nearest neighbor distance (in the horizontal dimension) in wavelengths is plotted as a function of the number of fish within the school in Figure 5, in which it is evident that the resonances from figure 4 appear to be at nearest neighbor distances that are integer multiples of half-wavelengths.

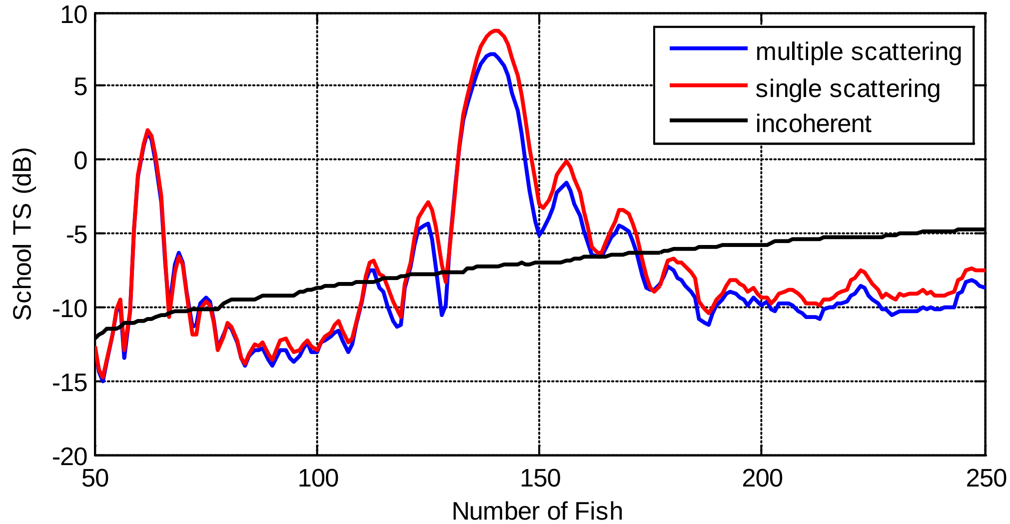

Figure 4. Example model outputs for the clustered fish schools at a frequency of 1000 Hz.

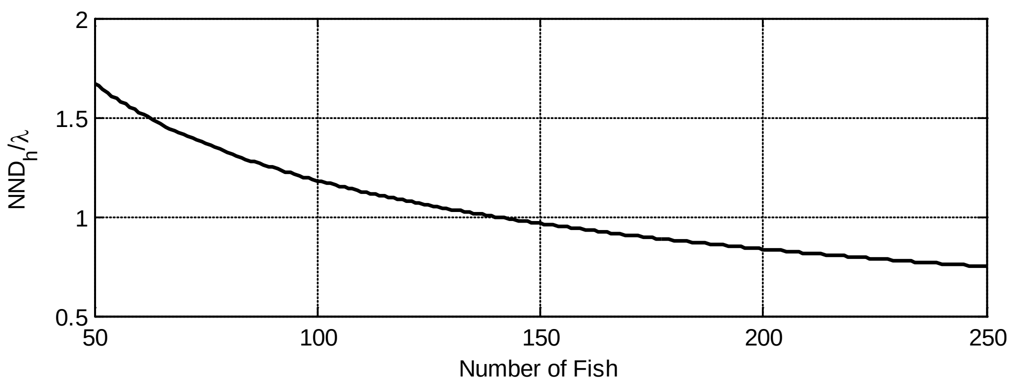

Figure 5. Nearest neighbor distance (in the horizontal dimension) in wavelengths plotted as a function of the number of fish.

Empirical Observations of Clustered Tuna

The difference in TS between the Poisson distributed (e.g. Figure 2) and clustered (e.g. Figure 4) school models is as much as 10-15 dB for the scenarios described here, and so it is important to understand which model better describes an actual tuna school. This is being examined using empirical data collected using both aerial imagery and high frequency multibeam sonar data. A focus of the last years work has been on manually classifying the aerial imagery. For each raw image (see Figure 6, left-hand side), the individual tuna are traced and uniquely classified (see Figure 6, right-hand side). The classified images are then analyzed to find their size, position (within the image), and orientation, allowing calculation of several stochastic school parameters: nearest neighbor distances, relative bearing (i.e., polarization), etc. A few hundred images have been processed and although this is a labor intensive process, the classified images provide two important results: 1) metrics describing

the schools that can be directly incorporated into the school models; and 2) a valuable training set for automated classification methods that can be used to expand this work.

Often, several subsequent images of the same fish school were collected. The resulting school metrics from one of these instances during which 13 images were collected are shown in Figure 7. The average (within a single image) nearest neighbor distances are shown to vary between 0.4 and 0.7 body lengths. For the approximately 1 m long fish imaged here, this would correspond to 0.4-0.7 meters. The number of observed fish varies from 159 to 263. The three final images show the lowest three observed number of fish and the largest nearst neighbor distance, which may be an indication of a behavior induced by the presence of the fishing vessel (see Figure 6, top left) and/or the airplane aquiring the images.

Although the empirical school data has not yet been incorporated directly into the acoustic models, the data can still be used to examine the question of which school model (Poisson distributed or clustered) matches reality more closely. Figure 8 shows a histrogram of the nearest neighbor distance (normalized by body length) for a single school in which 263 individual fish were observed. These data give a mean nearest neighbor distance of 0.48 body lengths with a standard deviation of 0.16 body lengths (or approximately 1/3 of the nearest neighbor distance), giving an indication that there is at least some level of clustering within the school that could give rise to the type of school resonances shown in Figure 4 (note that the standard deviation would be 0.29 if the fish had nearest neighbor distances uniformly distributed between 0 and 1 body lengths).

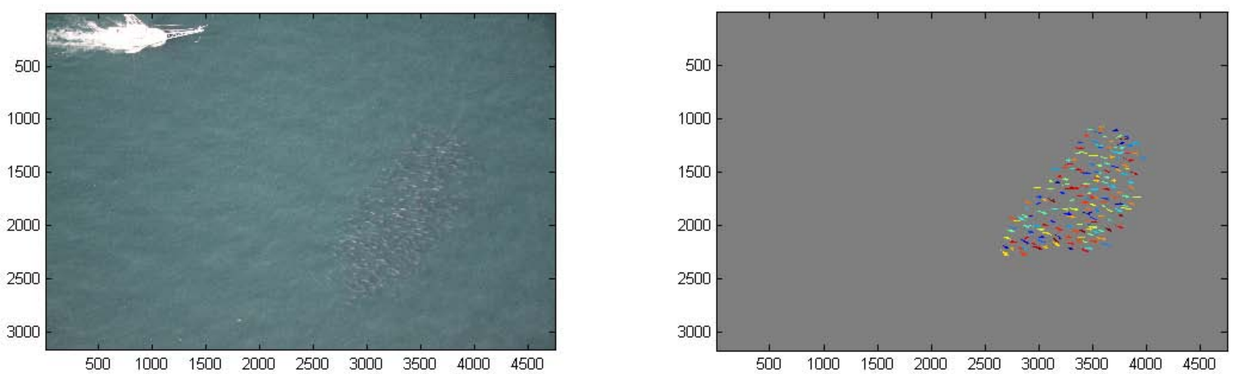

Figure 6. Raw aerial imagery (left) and manually classified image on the right. Note that each identified bluefin tuna is a unique color.

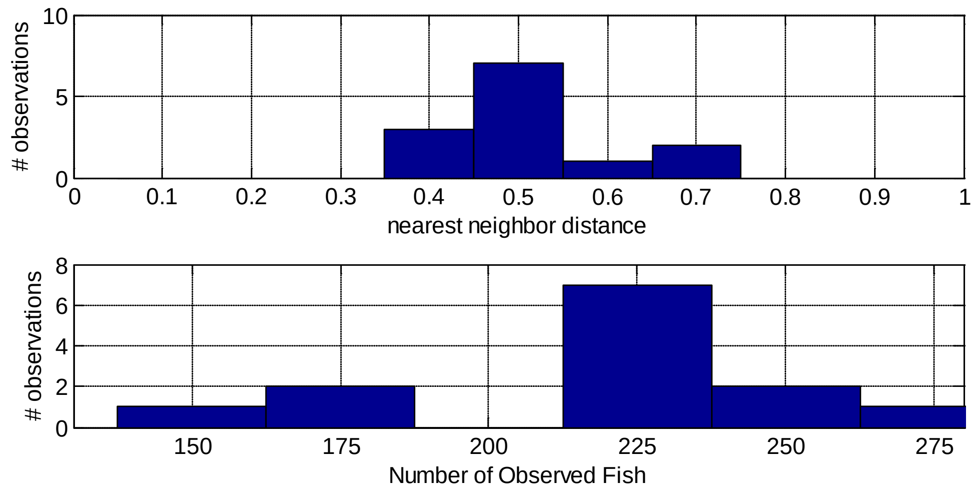

Figure 7. Example school metrics derived from the classified aerial imagery: nearest neighbor distance in body lengths (top) and number of observed fish (bottom). The data shown here represent 13 subsequent images of the same fish school.

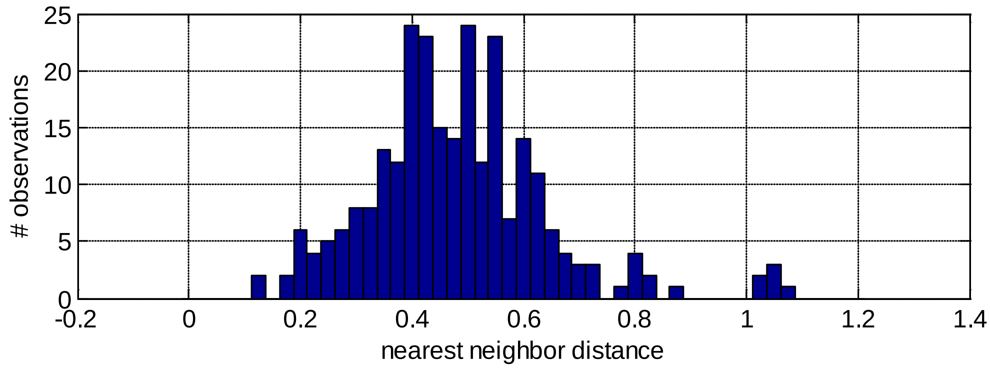

Figure 8. Nearest neighbor distances (normalized by body length) within a single school image.

IMPACT/APPLICATIONS

Accurate predictions of reverberation (both mean levels and higher order statistical moments) serve the community of scientists and engineers tasked with developing active sonar systems, increasing their ability to design hardware (e.g., select frequencies, power levels, system topologies for multi-static sensors), develop signal processing algorithms aimed at detection/classification/localization/tracking, estimate system performance, and design realistic sonar simulations.

RELATED PROJECTS

Acoustic assessment of juvenile bluefin tuna aggregations: a feasibility study. PI: Molly Lutcavage, UNH. Sponsor: Northeast Consortium.

Assessment of rockfish species in untrawlable habitats using advanced acoustic, optical, and trawl technologies. PI's: Chris Rooper, Alaska Fisheries Science Center, Tom Weber, University of New Hampshire, Dave Demer, Southwest Fisheries Science Center. Sponsor: North Pacific Research Board.

Effects of fishing on herring aggregations. PI: Jason Stockwell, Gulf of Maine Research Institute. Sponsor: National Marine Fisheries Service.

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